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The Design of Advanced Multi-Junction Solar Cells Using Genetic Algorithm for the Optimization of a SILVACO Novel Cell Model

The Design of Advanced Multi-Junction Solar Cells Using Genetic Algorithm for the Optimization of a SILVACO® Novel Cell Model.

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ASTRACT

MULTIJUNCTION solar cells consisting of series-stacked p-n junction layers offer a significant improvement in efficiency over conventional solar cells by generating power over a larger spectrum of sunlight. The design of multijunction solar cells is complicated by both the desire to have maximally efficient junction layers and the need to match the current produced in each junction layer under optimal load conditions. The ATLAS device simulator from Silvaco® International has been shown in exclusive research at the Naval Postgraduate School to have the capability to simulate multijunction solar cells. This simulation tool has the ability to extract electrical characteristics from a solar cell based on virtual fabrication of its physical structure and bypass the costly "build-and-test" design cycle. A paper introducing this modeling technique has been previously presented at the PVSC conference [2].

The current-matching problem is especially challenging for cells containing four or more junction layers. This paper proposes a method for using ATLAS data to optimize the power output of individual junction layers of an InGaP/GaAs/InGaNAs/Ge four junction solar cell and to construct these junction layers into a current-matched, optimum power multijunction solar cell. Individual junction layer optimization was accomplished through the use of a genetic search algorithm implemented in Matlab. The final multijunction cell current matching was performed using an iterative optimization routine also implemented in Matlab.

INTRODUCTION

The primary goal of multijunction solar cell design is to maximize the output power for a given solar spectrum. The construction of multijunction cells places the individual junction layers in series, thereby limiting the overall output current to that of the junction layer producing the lowest current. The solution to optimizing a multijunction design involves both the design of individual junction layers which produce an optimum output power and the design of a series-stacked configuration of these junction layers which yields the highest possible overall output current. This paper proposes a two-part process to refine a given multijunction solar cell design for near-optimal output power for a desired light spectrum.

THE MODELING SOFTWARE

The optimization routines described in this paper use a solar cell model developed at the Naval Postgraduate School using the ATLAS device simulator by Silvaco® International. This model predicts the electrical characteristics of a solar cell based on virtual fabrication of its physical structure, as shown in Figs 1 & 2 below.

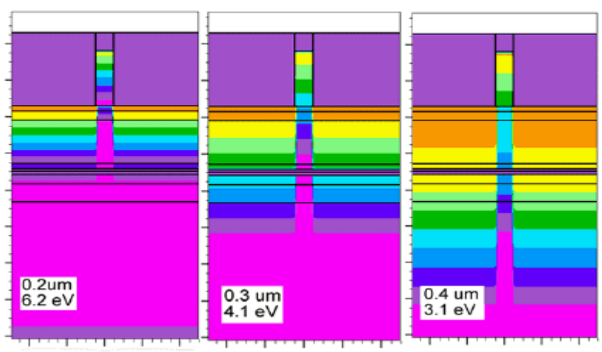

Figure 1. ATLAS photogeneration rate output for a multijunction cell.

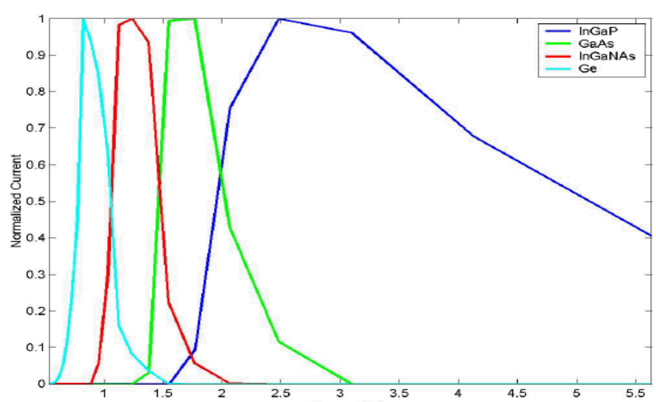

Figure 2. ATLAS spectral response output for a four junction solar cell.

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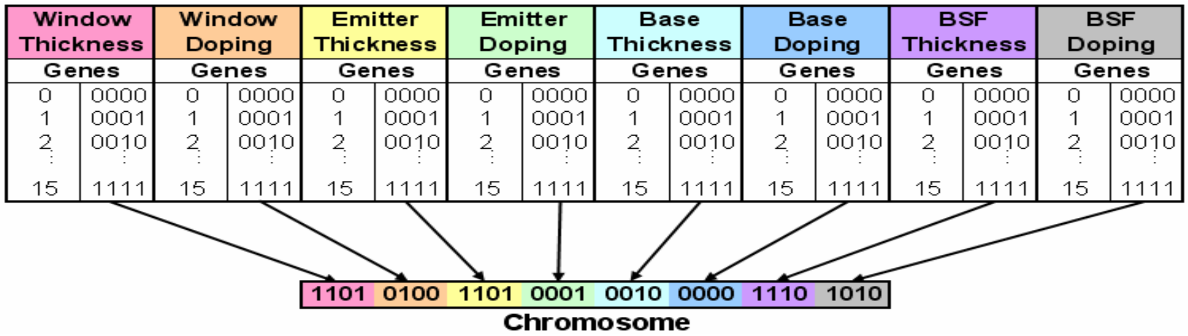

Figure 3. Construction of a binary chromosome from gene sequences.

THE GENETIC SEARCH ALGORITHM

The first step in the optimization process is to maximize the output power of each junction layer individually for several layer thicknesses. These optimum configurations will be used to ensure maximum junction layer output power as junction layer thicknesses are changed during the current-matching process. The junction layer optimization process accepts known materials for the window, emitter, base and back surface field (BSF) and determines the ideal thicknesses and dopings for each region. The base thickness was chosen to be a dependent variable to achieve a constant overall junction layer thickness. Thus, seven independent variables remain for each overall junction layer thickness. To search all possible solutions rigorously would require an enormous amount of computational time. Instead, a genetic algorithm was used to search the solution space for the junction layer configuration producing the highest output power. To enact a genetic algorithm for junction layer optimization, each of the eight variable junction layer parameters was encoded into a four-bit binary string. The encoded binary strings, referred to as genes, were then assembled into 32-bit binary chromosomes as illustrated in Fig. 3 above.

Each chromosome fully encoded the eight variable properties of a junction layer. A set of 35 randomly selected binary strings made up the initial generation of chromosomes. The encoded properties in each of these chromosomes were used to construct and simulate a junction layer in ATLAS under AM0 illumination. After the simulation of an entire generation of chromosomes, child chromosomes (to make up the next generation) were formed from a mix of the genes from the best performing parent chromosomes. Following this “breeding”, the chromosomes were subjected to a 1% probability single bit mutation. In addition, the best performing chromosome of each generation was passed unchanged onto the next generation.

The genetic search algorithm was initially allowed to progress for a maximum of 20 generations. This scheme allowed a solution space of over 268 million junction layer designs to be searched to arrive near an optimal junction layer configuration for a specific thickness (Fig. 4) in a reasonable amount of time.

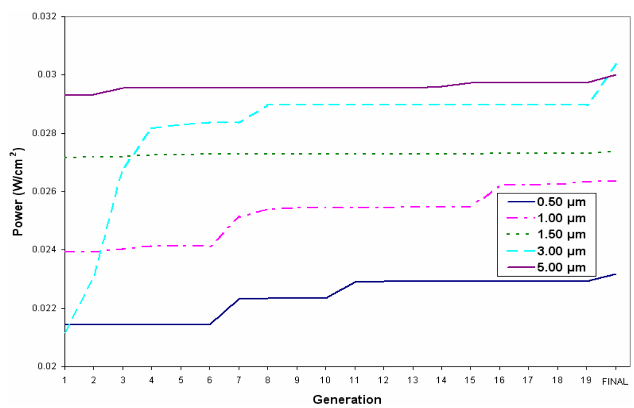

Figure 4. Improvement of GaAs junction layer.

In subsequent attempts, a distributed computing scheme was used to distribute the workload to multiple computers. This allowed the simulation to run for 50 generations in a significantly shorter time period. The result showed that the genetic algorithm certainly produced better results given more computation time. For the 50 generation runs, the mutation rate was increased considerably in order to prevent the population from completely converging.

ITERATIVE CURRENT-MATCHING ROUTINE

To achieve a maximum overall output current from the full multijunction cell, the current produced by each junction layer needed to be matched to the fullest extent possible. To accomplish this, we used an iterative current-matching routine beginning with an ATLAS simulation of the full multijunction cell with each junction layer thickness larger than its estimated final thickness. In this initial state, each junction layer absorbed a large amount of light and little light energy was able to penetrate to each lower junction layer successively.
To match short-circuit currents, junction layers were grouped into pairs from the top junction to the

substrate junction (Fig. 5). Short-circuit currents were matched within the pairs by either increasing or decreasing the thickness of the upper junction layer. Then the junction layers were re-grouped with the other adjacent junction layer and the process repeated iteratively until the short-circuit currents of all junction layers were within 99.6% of each other.

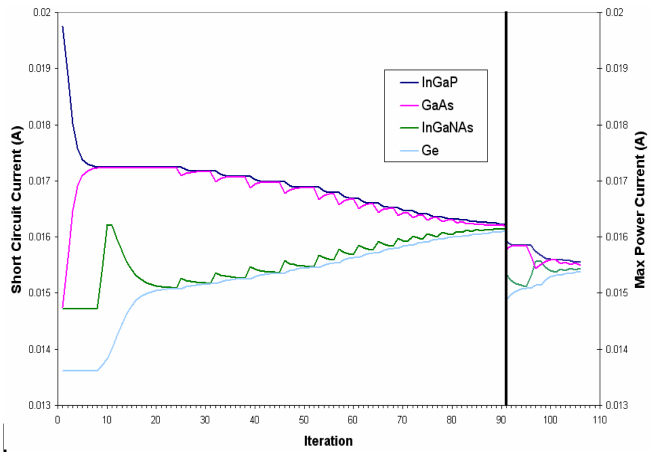

Figure 5. Progress of iterative current matching.

At this point, the routine changed focus to attempt to match the maximum-power currents of the individual junction layers. The routine ceased when all junction layer maximum-power currents were matched. The optimum cell configuration could then be determined by a review of the output file for the cell with the highest overall maximum power (Fig. 6,7).

It was necessary to ensure that each junction layer performed optimally at each of the many thicknesses used in the iterative current-matching routine. This was accomplished by using the optimized parameters from the genetic search algorithm for each junction layer. When a junction layer thickness was required that had not been specifically solved for during junction layer optimization, interpolation between known optimum values was used.

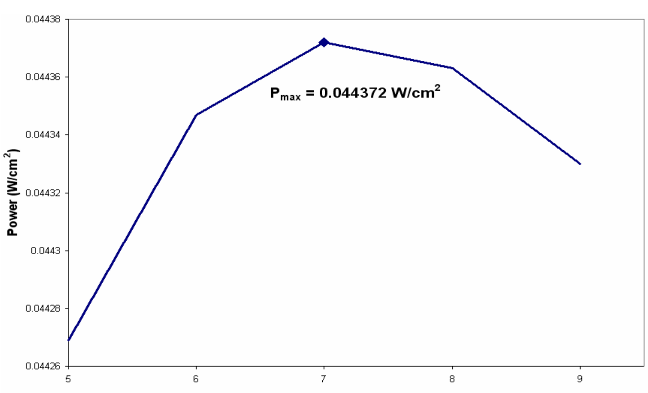

Figure 6. Optimum 3-junction power.

RESULTS

For obvious reasons of propriety, no published reports on the detailed construction of advanced

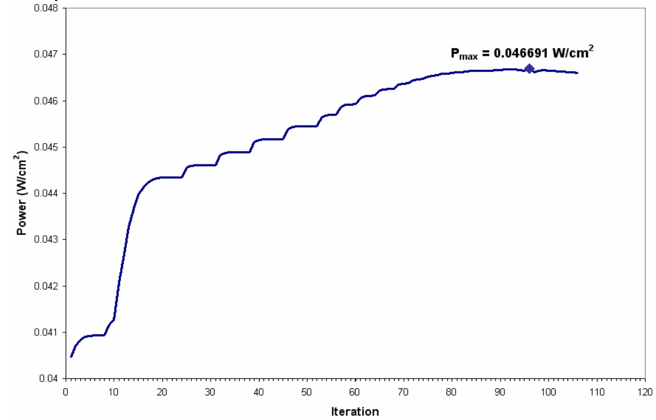

Figure 7. Optimum 4-junction power.

three- and four-junction solar cells could be found. This lack of an experimental baseline complicates any attempt to show the improvement over a tested design obtained by using the optimization procedure proposed in this paper. The usefulness of this technique is instead demonstrated using unpublished three- and four-junction solar cell designs that have been realized using ATLAS. The four-junction cell structure used in this model is shown in Fig. 8 below.

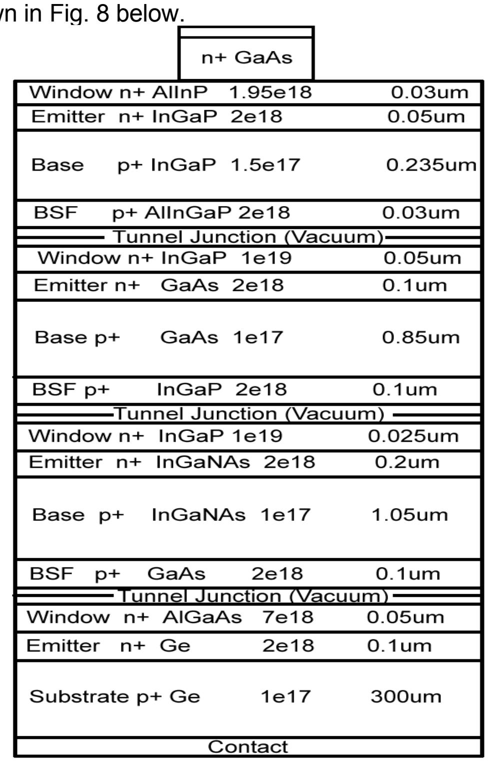

Fig. 8. InGaP/GaAs/InGaNAs/Ge cell as simulated.

Figs. 9 and 10, below demonstrate the *IV* curves of the optimized three and four junctions structures using the SILVACO models and the Genetic Algorithms. While achieved optimized cell output parameters are listed in Table 1.

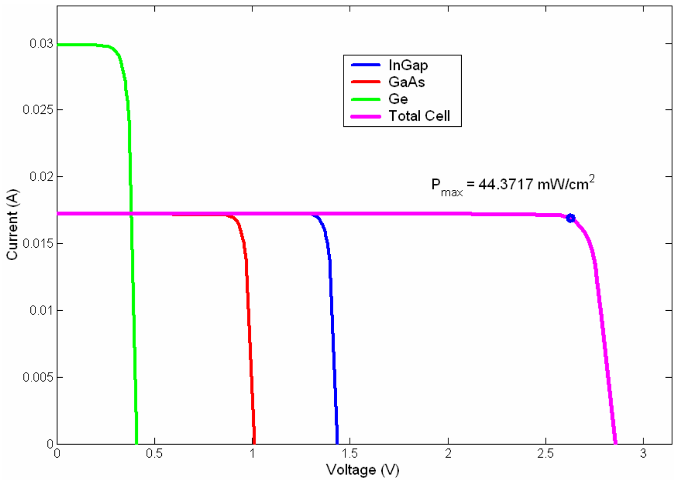

Figure 9. I-V curve for optimized 3-junction.

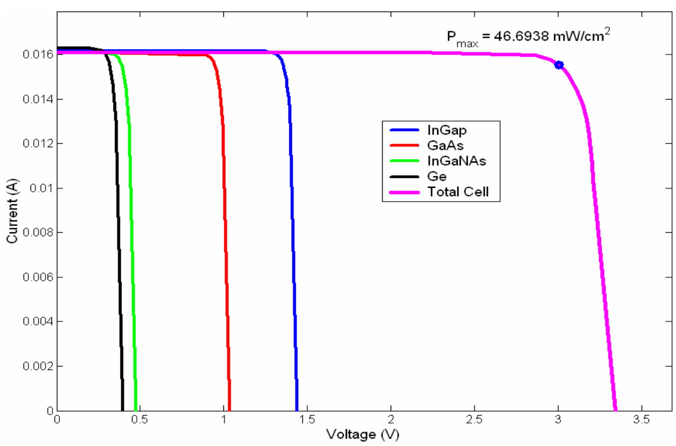

Figure 10. I-V curve for optimized 4-junction.

Table 1. Output Power Improvement Following Iterative Current Matching Routine

	Triple Junction			Quad Junction		
	Original	Current-Matched	Fully Optimized	Original	Current-Matched	Fully Optimized
Short Circuit Current I_{sc}	15.28	16.99	17.25	15.40	16.45	16.09
Open Circuit Voltage V_{oc}(V)	2.73	2.74	2.86	3.24	3.19	3.35
Max Power Current I_{mp} (ma)	15.10	16.63	16.91	14.99	16.03	15.53
Max Power Voltage V_{mp} (V)	2.52	2.49	2.62	2.90	2.82	3.01
Fill Factor FF(%)	91.51	86.07	90.01	87.29	86.07	86.77
Maximum Power P_{max} (mW/cm^2)	38.11	41.43	44.37	43.53	45.19	46.69
Efficiency η(%)	27.88	30.31	32.47	31.85	33.07	34.16

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